A Single-Sideband Short-Wave System for Transatlantic Telephony *

By F. A. POLKINGHORN and N. F. SCHLAACK

This paper describes the construction of a short-wave single-sideband reduced-carrier system of radio transmission. It also reports the results of comparisons made between this system and an ordinary short-wave double-sideband system between England and the United States. It was found that the single-sideband system gave an equivalent improvement in radiated power over the double-sideband system averaging 8 db. This is in good agreement with the theoretical improvement to be expected.

INTRODUCTION

THE single-sideband suppressed-carrier method of transmission has been used to effect economies in the power capacity required, energy consumed, and space in the frequency spectrum on carrier telephone circuits for over fifteen years. On the basis of equal peak amplitudes in a transmitter a single-sideband suppressed-carrier system gives a possible theoretical improvement of 9 db in received signal-to-noise ratio over a double-sideband and carrier system. Six db of this improvement is obtained by omitting the carrier and utilizing the entire available amplitude capacity of the transmitter for the sideband. The other 3 db is obtained by reducing the band width of the receiver to only that required to pass one sideband, thus reducing the noise energy at the receiver output by one-half.

In order that speech may be transmitted without undue distortion over a single sideband system, it is necessary that the carrier frequency at the receiver be within about ± 20 cycles of the correct value. For the transmission of music a much higher precision is required. The practical construction of a single-sideband radio system at frequencies of the order of 60 kc., such as is used in the long-wave transatlantic telephone circuit, requires only a careful application of known technique to obtain the desired degree of stability of the oscillators. At the short-wave transatlantic radio telephone frequencies of from 5,000 to 20,000 kc., however, the very best crystal oscillators, such as are now used only for the very highest quality laboratory standards, would be required at both transmitter and receiver to obtain the degree of synchronization required.

This high degree of frequency stability can be dispensed with by

---

* Published in *Proc. I.R.E.*, July, 1935.

transmitting a pilot frequency over the channel. For this purpose the carrier frequency serves as well as, if not better than, any other frequency since it is easily obtainable at the transmitter and is readily utilized at the receiver. If a single-sideband transmitter is fully loaded by two equal side frequencies and a carrier of amplitude 10 db below one of the side frequencies, the power in the carrier is only about 5 per cent of the power in the side frequencies. If the peak voltage in the transmitter is kept the same, each side frequency could be 1.3 db greater when no carrier is transmitted. Practically, it is found that since distortion rather than peak voltage is the limiting factor, the presence of the carrier 10 db down has no appreciable effect on the permissible sideband amplitude. By using a very narrow filter at the receiver to pass the carrier, the same carrier-to-noise ratio can be obtained with the reduced carrier as is ordinarily obtained with a common double-sideband receiver receiving a carrier of full strength. After passing through this narrow filter the carrier may be used to synchronize automatically a local carrier, or by amplifying to a greater extent than the sideband and recombining with the sideband, it may be used for direct demodulation of the sideband. When used in the latter manner it will be called "reconditioned carrier."

In 1928, after extensive tests of short-wave double-sideband transmission had been conducted[1] and while the short-wave transatlantic telephone channels between the United States and England were under construction, some preliminary trials of a short-wave single-sideband system were made under the direction of Mr. R. A. Heising between Deal, New Jersey, and New Southgate, England, using a local carrier supply at the receiver. The local carrier was produced by beating the output of a variable-frequency tuned-circuit oscillator with that of a crystal oscillator. It was necessary to adjust the oscillator continuously in order to keep the oscillator frequency in the proper relation to the incoming sideband.

Notwithstanding the limitations of the equipment, encouraging results were obtained and study of the problem was continued, although along a slightly different line. Receivers were built which were capable of separating the sidebands and carrier of an ordinary double-sideband and carrier transmission in such a manner that single-sideband and other types of reception could be simulated. The carrier could be separately filtered and reconditioned so that even with

---

[1] Reports of some of these tests were contained in the following articles: "Some Measurements of Short Wave Transmission," R. A. Heising, J. C. Schelleng and G. C. Southworth, *Proc. I. R. E.*, October, 1926. "Transmission Characteristics of a Short-Wave Telephone Circuit," R. K. Potter, *Proc. I. R. E.*, April, 1930. "The Propagation of Short Radio Waves over the North Atlantic," C. R. Burrows, *Proc. I. R. E.*, September, 1931.

considerable selective fading a satisfactory carrier was continuously available. Tests made with these receivers showed that the elimination of one sideband at the receiver did not affect the intelligibility or quality of reception to any extent if allowance were made for the reduction in the received power.

DESCRIPTION OF APPARATUS

For the purpose of obtaining more complete quantitative information on the improvement to be realized from single-sideband operation and a better understanding of the requirements of commercial single-sideband equipment, apparatus was constructed for a trial of a short-wave single-sideband system across the Atlantic. Transmitter input equipment was constructed which was capable of delivering a single-sideband signal to the input of the water-cooled amplifiers used in the short-wave double-sideband transmitters. This input equipment was sent to Rugby, England, and with the cooperation of the British Post Office installed in conjunction with one of the transatlantic transmitters. For comparison purposes the normal double-sideband output of this same transmitter was used. A single-sideband receiver having a number of novel features was also constructed and installed at the transatlantic receiving station at Netcong, New Jersey. During the latter part of 1933 and the early part of 1934 comparative tests of double and single-sideband transmission were conducted between the British Post Office Headquarters in London and the Bell Telephone Laboratories in New York City.

Transmitting Input Equipment

Figure 1 shows a rear view of the transmitting input equipment. The equipment is mounted on three bays of panels in two welded steel cabinets, each panel being the width of the usual telephone relay rack panel. A schematic of the input equipment is shown in Fig. 2. The incoming speech is applied to the balanced modulator No. 1, to which is also applied voltage having a frequency of 125 kc., obtained through a multivibrator from a 625 kc. crystal oscillator. The low-frequency filter following the first modulator is of the lattice type of construction and uses quartz crystals as elements [2] in order to obtain the necessary attenuation to the carrier frequency and one sideband while passing the other sideband. This filter passes frequencies from 125.1 kc. to 130 kc. The unwanted sideband is suppressed from 40 to 60 db and

---

[2] For information on the construction of such filters, see article by W. P. Mason, "Electrical Wave Filters Employing Quartz Crystals as Elements," *Bell Sys. Tech. Jour.*, Vol. XIII, No. 3, July, 1934.

the carrier is suppressed approximately 20 db in the modulator and about 15 db more in the filter. In order to obtain a variable amplitude of carrier for experimental purposes, an arrangement was provided for by-passing a variable quantity of the carrier around the first modulator and low-frequency filter. The single-sideband voltage obtained from

Fig. 1—Rear view of single-sideband transmitting input equipment.

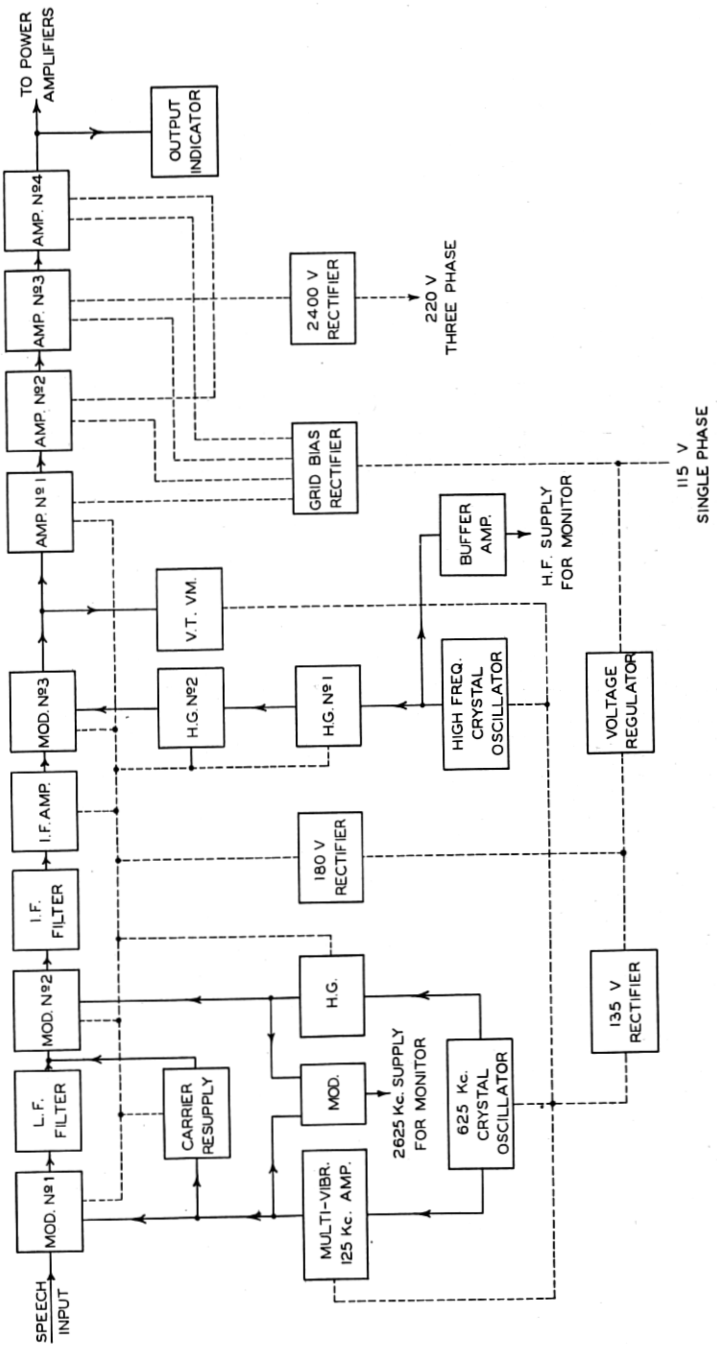

Fig. 2—Schematic of single-sideband transmitting input equipment.

the low-frequency filter, together with the reintroduced 125 kc. carrier, is impressed on the input of balanced modulator No. 2. A 2,500 kc. carrier voltage, which is obtained from the 625 kc. crystal oscillator by means of a harmonic generator, is also supplied to the input of the second modulator. The intermediate frequency filter which follows the second modulator passes the upper sideband generated in the second demodulator (from 2,625.1 to 2,630 kc.) and suppresses the other sideband and the carrier approximately 50 db. The single sideband thus obtained is then amplified before it is impressed on the input of the third modulator. The circuits up to and including the intermediate amplifier are fixed and do not have to be adjusted in order to change the final output frequency of the equipment. The third modulator is of the unbalanced type and both the output of the intermediate frequency amplifier and a third carrier are applied to its input. The third carrier is obtained from a high-frequency crystal oscillator through two harmonic generators in tandem. The frequency of the carrier applied to the third modulator depends on the output frequency desired and since either sideband may be selected the carrier frequency must be 2,625 kc. greater or less than the desired final output carrier frequency. In order to cover the range from 4,700 kc. to 21,000 kc., the carrier must range from 7,325 to 18,375 kc. No filter is required in the output of the third modulator since the output tuned circuits are narrow enough to exclude the third carrier and the unwanted sideband, which are respectively 2,625 and 5,250 kc. away from the desired sideband. The output circuit of the third modulator is the first point in the equipment where the final frequency to be transmitted is obtained. The output voltage of the third modulator is applied to the input of a series of four amplifiers in tandem, which serve to increase the amplitude of the single sideband and the reduced carrier to a value which will excite to full capacity the power amplifiers of a regular double-sideband transmitter. Receiving type screen-grid tubes are used in all but the multi-vibrator, crystal oscillator and the final amplifiers. Amplifiers 2 and 3 consist of one 75-watt screen-grid tube each and amplifier 4 consists of two 1-kw. screen-grid tubes in push-pull.

Transmitting Monitor

It is extremely important in operating the single-sideband equipment to know that the distortion is within reasonable limits. With the ordinary double-sideband type of transmission it is possible to simulate the receiving equipment with a very simple rectifier, thus allowing local distortion tests to be made on the transmitter. With single-sideband transmissions in which the carrier is either totally or partially suppressed such a simple receiver is not adequate, as the distortion produced in a simple rectifier would be excessive. It is necessary that a carrier of the right frequency and of an amplitude considerably greater than that of the sidebands be present in the rectifier. After a study of the situation it was decided to build up the carrier for monitoring purposes from the same crystal oscillators used in the transmitter. The monitoring device, a schematic of which is shown in Fig. 3, consists of two detectors and a harmonic generator

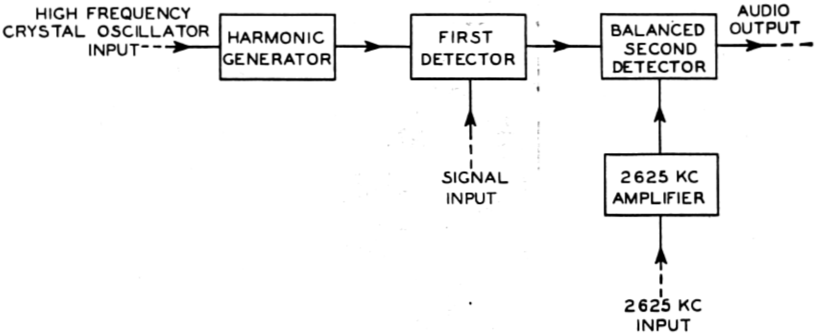

Fig. 3—Schematic of transmitting monitoring device.

which take the high-frequency carrier and combine it with the signal to produce an intermediate frequency, which is in turn beaten with the 2,625 kc. derived from the low-frequency carrier crystal to obtain a demodulated voice frequency.

Receiver

The front view of the receiver is shown in Fig. 4. The receiver is mounted in a steel cabinet seven feet high and a standard telephone bay in width. Figure 5 shows a block schematic of the receiver. The receiver is of the usual double-detection variety, having a high-frequency amplifier stage, a balanced first detector, a three-stage intermediate frequency amplifier and a balanced second detector. A branch circuit, taken from the grid of the third intermediate frequency amplifier tube, contains a narrow crystal filter which passes the carrier, but not the sideband. After passing through the filter the carrier is amplified and rectified by a linear rectifier, the rectified output giving automatic volume control action on the high-frequency tube, first detector, and first and second intermediate frequency amplifiers. Another branch circuit passes the filtered carrier through an overloaded amplifier which reduces the fluctuations of carrier amplitude which may be present due to fading or modulation. This reconditioned carrier is then used for obtaining automatic frequency control of the beating oscillator and synchronization of the local carrier oscillator, or it may be applied directly to the second detector for demodulation purposes.

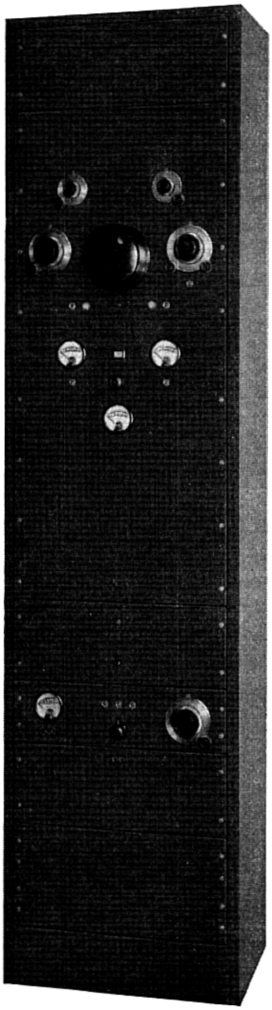

Fig. 4—Front view of single-sideband receiver.

By using an intermediate frequency band of moderate width, an ordinary double-detection receiver for double-sideband operation

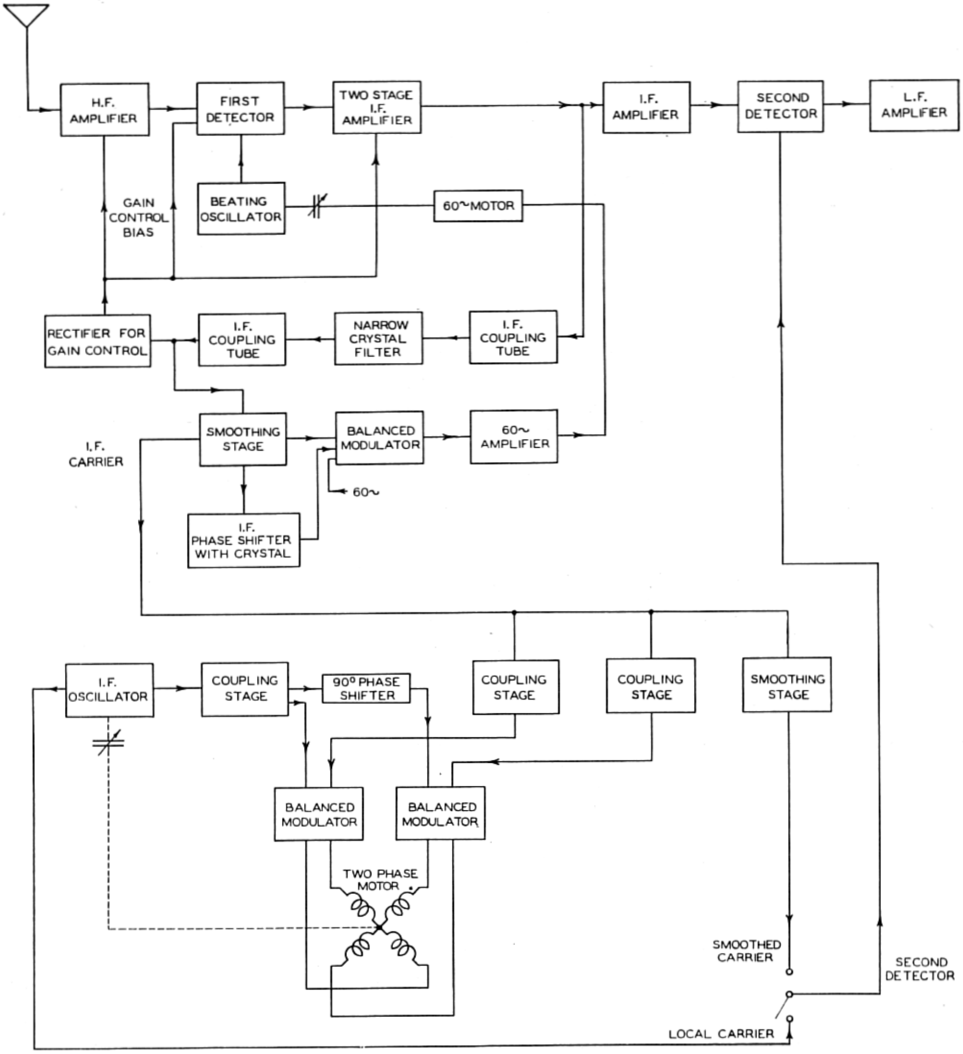

Fig. 5—Schematic of single-sideband receiver.

may be built which will require tuning of the beating oscillator at very infrequent intervals, perhaps only two or three times a day. For receivers in which the carrier is to be separated from the sideband by a narrow filter, a much higher degree of frequency stability is required in both the transmitter and the receiving beating oscillator if frequent or almost continuous tuning is to be avoided. Rather than endeavor to obtain the high-frequency stability required, it was decided to arrange that the incoming carrier automatically tune the beating oscillator of the receiver in such a manner that the carrier at intermediate frequency would always pass through the narrow crystal filter in a satisfactory manner. The manner in which this is accomplished is shown in Fig. 6. The reconditioned carrier is introduced in push-pull fashion on the grids of a balanced modulator system. The same carrier is passed through a circuit having a 90-degree phase shift, through a narrow band suppression filter, and applied to the same two grids in parallel. A small 60-cycle voltage is also applied to the grids in parallel. The 60-cycle output voltage of the balanced modulators is applied through a transformer to the rewound current coils of a watt-hour meter. When the carrier frequency is that of maximum suppression for the narrow filter, equal voltages e_1 and e_2 will be applied to the grids of the two tubes forming the balanced modulator. If the carrier frequency shifts from this position, the voltage applied to each grid will be the vector sum of e_1 or e_2 and a voltage of variable magnitude and phase e_ϕ, which appears in parallel on the two grids. The

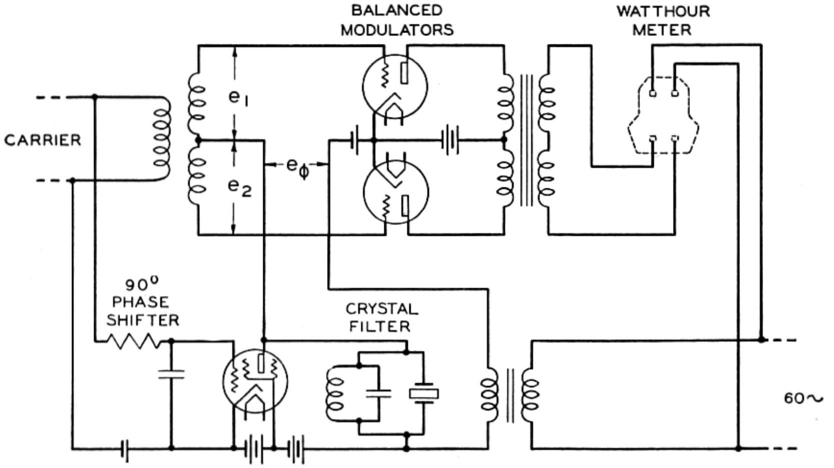

Fig. 6—Schematic of automatic tuning device.

magnitude of e_ϕ voltage increases as the frequency of the carrier at intermediate frequency departs from its proper value, causing the voltages on the two grids to change, one becoming higher than the other as shown by $e_1 + e_\phi$ and $e_2 + e_\phi$ of Fig. 7. As the amplitude of the applied radio frequency voltage increases, the mutual conductance of the modulator tube decreases and consequently a greater amount of 60-cycle current flows in the plate circuit, the phase of which depends upon which tube has the higher mutual conductance. The voltage coil of the watt-hour meter is permanently connected to the supply lead. When the frequency of the carrier at intermediate frequency is too high, the phases will be such that the watt-hour meter runs in one direction, and when the frequency of the carrier is too low the watt-hour meter runs in the other direction. A very small condenser is substituted for the registering mechanism of the watt-hour meter. This condenser is connected to the beating oscillator circuit and the whole circuit arranged in such a manner that the watt-hour meter runs

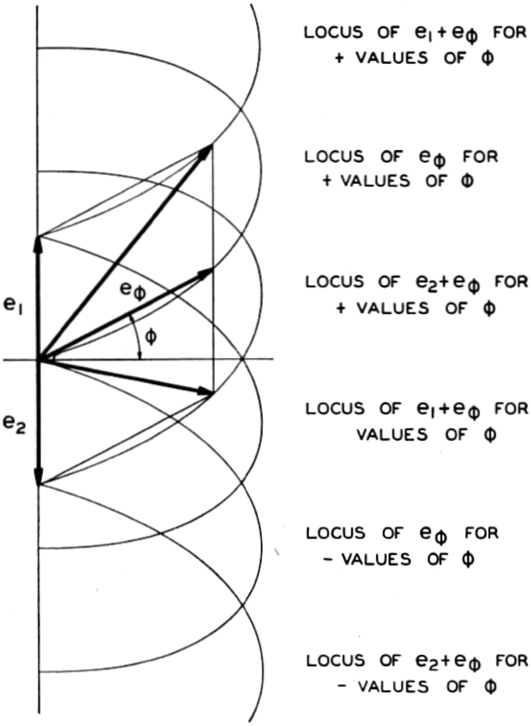

Fig. 7—Vector diagram of input voltages to balanced modulators of the automatic tuning device.

until the beating oscillator gives the proper frequency, when the action stops.

Since this automatic tuning unit holds the carrier at intermediate frequency in a fixed relation with respect to a crystal filter, which may drift slightly in resonant frequency from time to time, and not in synchronism with a local carrier oscillator, it is necessary that a separate mechanism be provided for synchronizing the local carrier if a local carrier is to be used. A schematic diagram of the circuit for doing this is shown in Fig. 8. The reconditioned carrier at intermediate frequency is introduced through amplifiers to two balanced modulators. The output of the local carrier oscillator is introduced to the same modulators, to one of them directly and to the other through a device which shifts the phase 90 degrees. The phases of

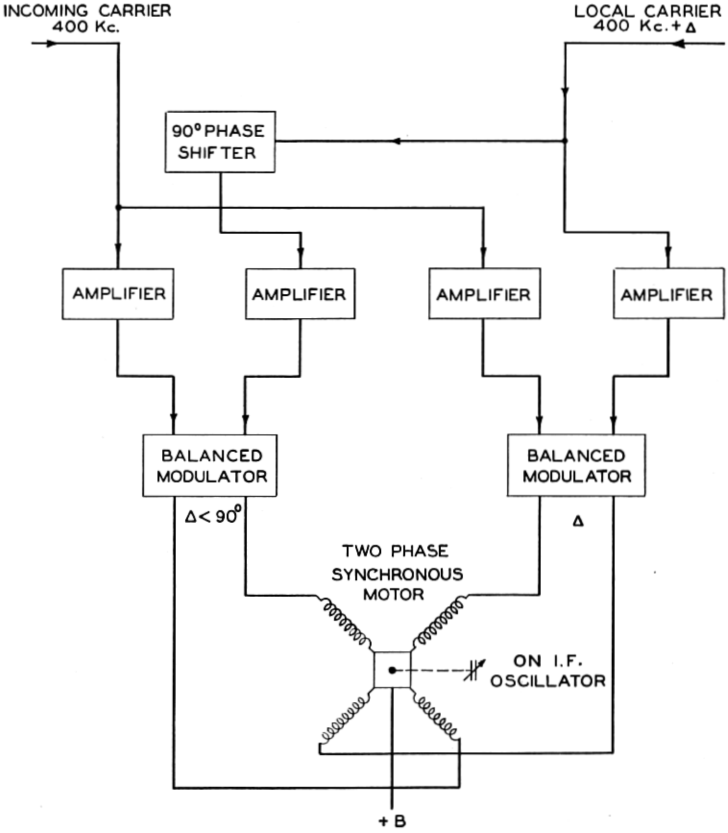

Fig. 8—Schematic of automatic synchronizing equipment.

the outputs of these balanced demodulators will be in quadrature and the frequency will be the beat frequency, Δ, between the incoming and local carriers. These voltages operate a variable reluctance type synchronous motor [3] which is mechanically connected to a condenser which forms a part of the local carrier oscillator circuit. The motor operates until the frequency of the local carrier oscillator is exactly the same as the carrier at intermediate frequency, when the frequency applied to the two-phase motor becomes zero.

For distortion testing the receiver can be used as an harmonic analyzer, the frequency of the beating oscillator being shifted so that only the desired distortion product passes through the narrow crystal filter. Measurements made in this way when the transmitter and receiver were close together checked very well with measurements made using the monitoring unit previously described.

A balanced second demodulator system was used, as the distortion is much less than with other types. No attempt is made to separate the incoming carrier from the sideband in the second demodulator, the amplitude of the reconditioned carrier or the local carrier supplied to the second demodulator being several times the amplitude of the carrier transmitted with the sidebands.

Experimental Results and Discussion

To determine experimentally in a quantitative manner the relative merits of two radio systems, such as the single and double-sideband systems, is a matter of considerable difficulty. However, as a practical matter, the percentage of increased commercial time and the increased satisfaction which a customer may obtain are of great interest. Three types of tests have been used in the past for rapidly obtaining information on the performance of radio circuits. They are: (*a*) determining the signal-to-noise ratio, (*b*) articulation tests, and (*c*) observations of circuit merit.

A measurement of the signal-to-noise ratio is made by modulating the transmitter a given amount and measuring the tone at the receiving point. The tone is then removed and the noise measured with the same equipment. When fading conditions are severe a considerable degree of skill is needed to obtain consistent measurements.

Articulation tests may be made in the manner which has been described by Fletcher and Steinberg.[4] They may consist of the reading and recording of meaningless syllables, carefully chosen words inserted

---

[3] U. S. Patent No. 1,959,449.

[4] "Articulation Testing Methods," H. Fletcher and J. C. Steinberg, *Bell System Technical Journal*, October, 1929.

in a variety of sentences, or a simple list of words chosen at random and inserted in a common phrase.

In the routine operation of the transatlantic channels, the operators record a value of "circuit merit" which is a composite figure representing the operator's judgment of the commercial value of the circuit. All three of these types of test were used in comparing the single and double-sideband systems.

All observations were made on 9,790 kc. with an audio-frequency band of from 250 to 2,800 cycles. The carrier during single-sideband transmissions was 10 db in amplitude below one of two equal side frequencies which loaded the transmitter to its maximum amplitude capacity. Only a single tone was used to modulate the transmitter when measuring signal-to-noise ratios. The degree of modulation of the double-sideband comparison signal was 45 per cent when tone modulation was used. Speech modulation was made the same as for two tones for both double and single-sideband transmissions. Directional antennas were used for both transmitting and receiving. Successive observations were made on single and double-sideband trans-

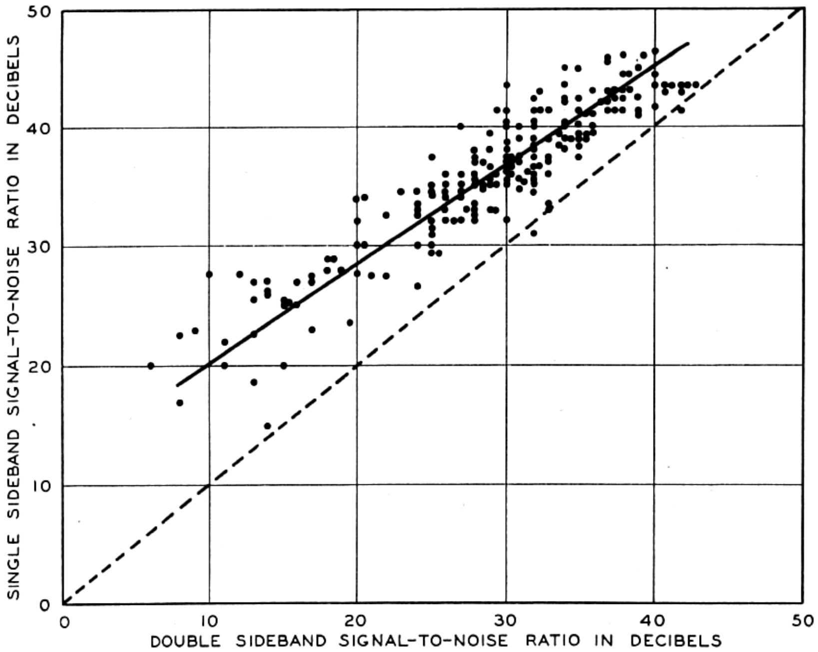

Fig. 9—Plot of signal-to-noise ratios on double sideband vs. signal-to-noise ratios on single sideband.

missions for 9-minute intervals. A reconditioned carrier was used at the receiver most of the time on account of the time required to synchronize the local oscillator when changing from double to single-sideband reception. The signal-to-noise ratio as well as the articulation was found to be the same for either reconditioned or local carrier except when the fields were very low, at which times the local carrier was found to be more satisfactory. Since it was convenient to use a slightly different degree of modulation on double-sideband than on single-sideband transmissions and the filter on the single-sideband receiver passed only 1.2 db less noise than the double-sideband receiver rather than the theoretically possible 3 db, a theoretical difference of 8.1 db instead of 9 db in signal-to-noise ratio was to be expected.

Each point shown on Fig. 9 represents the signal-to-noise ratio which was observed on the single-sideband system at a particular period plotted against the average of the preceding and succeeding values of signal-to-noise ratio measured on the double-sideband system. It will be seen that when the signal-to-noise ratio on the double-sideband system was 10 db the average signal-to-noise ratio

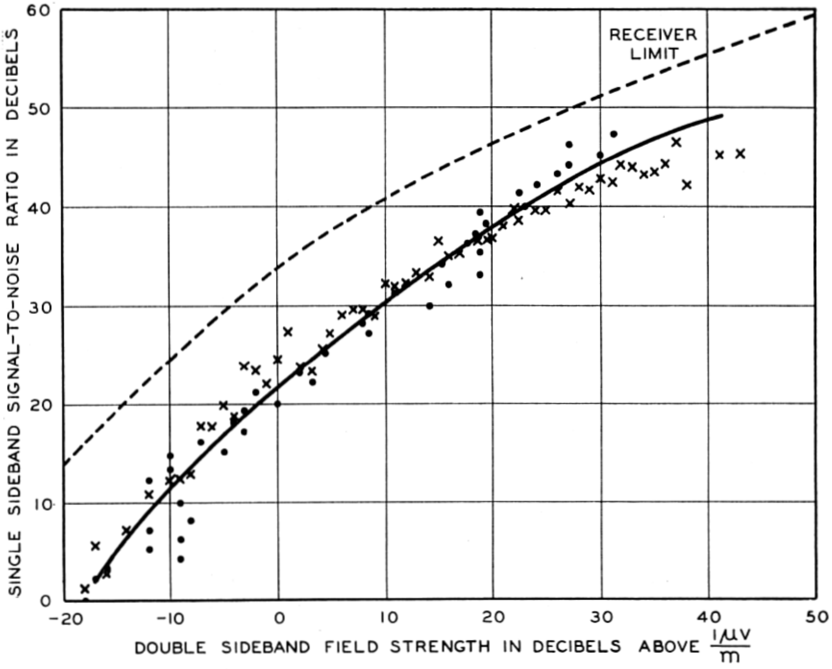

Fig. 10—Plot of signal-to-noise ratios on single sideband vs. field strength.

on the single-sideband system was 10 db higher, and when the signal-to-noise ratio on the double-sideband system was 40 db the average signal-to-noise ratio on the single-sideband system was 5 db higher. The lesser improvement with the single-sideband system for the higher signal-to-noise ratios was probably due to limitations in the maximum signal-to-noise ratio obtainable from the transmitting equipment.

Figures 10 and 11 are plots of the average signal-to-noise ratio versus field for the single and double-sideband systems. Only double-sideband fields were measured and the average single-sideband signal-to-noise ratios are plotted against the average of the preceding and succeeding double-sideband measurements. The crosses shown on the curve are the averages of all signal-to-noise ratios in 1 db intervals of field and the dots shown are averages of all fields obtained when the signal-to-noise ratio lay within 1 db intervals. The dotted lines represent the maximum signal-to-noise ratio which the receivers will give for various values of field. It is seen that on the average the set-noise was not the limiting factor determining the signal-to-noise ratios obtained.

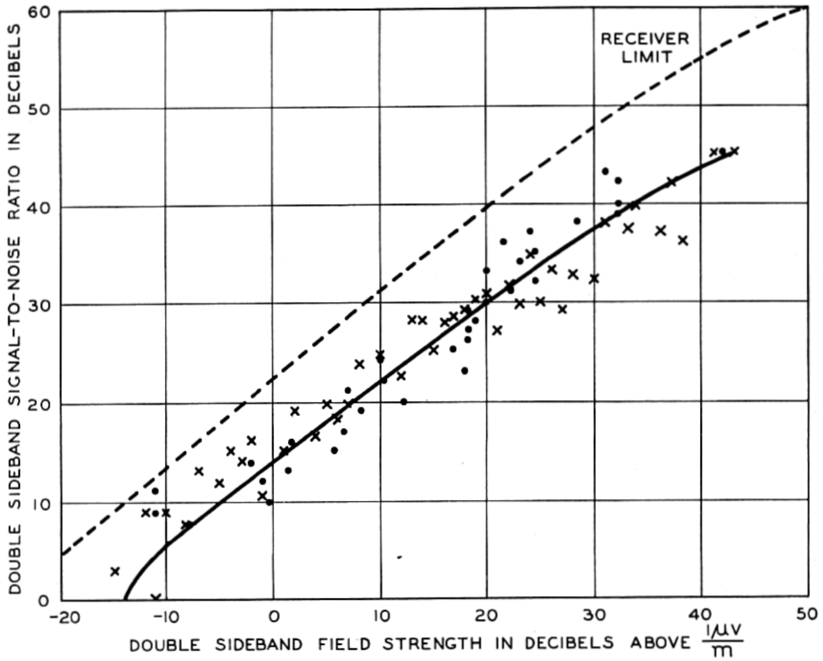

Fig. 11—Plot of signal-to-noise ratios on double sideband vs. field strength.

Upon occasions, advantages considerably higher than the average were obtained for the single-sideband system. Reeves[5] has shown that at times the two sidebands of a double-sideband radio system are likely to be shifted in phase relative to each other and the carrier in such a manner that the demodulated audio-frequency components add at random rather than directly in phase. Under such circumstances the received signal-to-noise ratio of the transmissions would be reduced by 3 db, and in comparison with the single-sideband system the latter would show a correspondingly greater improvement. Further, under bad fading conditions, some advantage might be expected from using a receiver in which provision is made to insure an adequate carrier in the second detector at all times. The single-sideband receiver used in these tests had such provision while the double-sideband receiver did not.

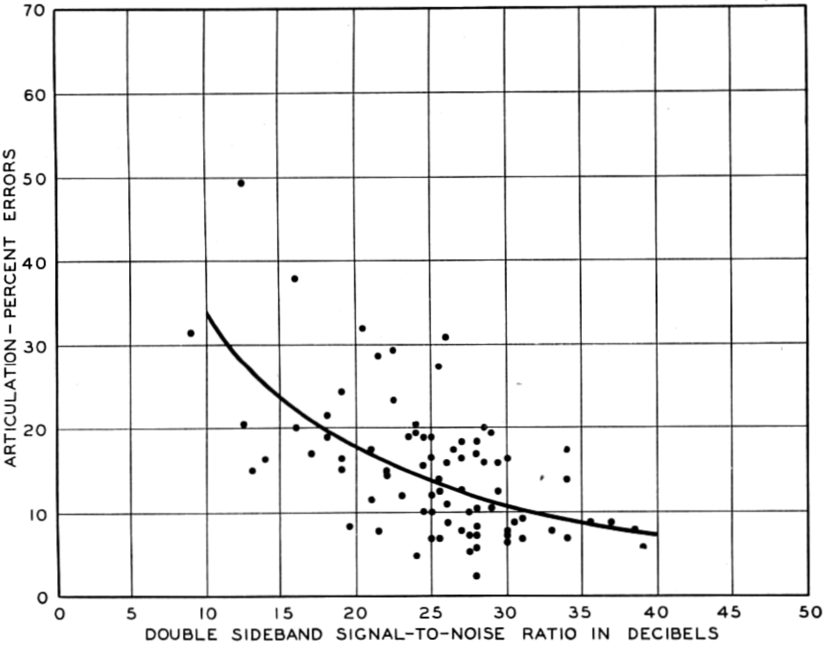

Fig. 12—Plot of per cent articulation errors on single-sideband vs. double-sideband signal-to-noise ratios.

The articulation of the two systems was compared by using words, which averaged approximately three syllables, taken at random from the dictionary. They were inserted in the phrase "Write down

---

[5] *Journal of the Institution of Electrical Engineers*, September, 1933, page 245.

. . . ". Native English callers were used at the transmitting end of the circuit almost exclusively and experienced articulation observers were used at the receiving end. Figures 12 and 13 show the articulation errors observed on the single and double-sideband transmissions plotted against the signal-to-noise ratios measured on the double-sideband receiver. When plotting the single-sideband data, the average of two successive signal-to-noise ratio readings on double-sideband was taken as the signal-to-noise ratio for plotting the intervening single-sideband observation. The improvement due to the use of the single-sideband system expressed in decibels is the difference in the abscissæ of the two curves for a given ordinate. The second curve of Fig. 12 has been dotted in on Fig. 13 to facilitate the comparison of the two systems. The improvement is seen to average about 8 db for intermediate values of signal-to-noise ratio.

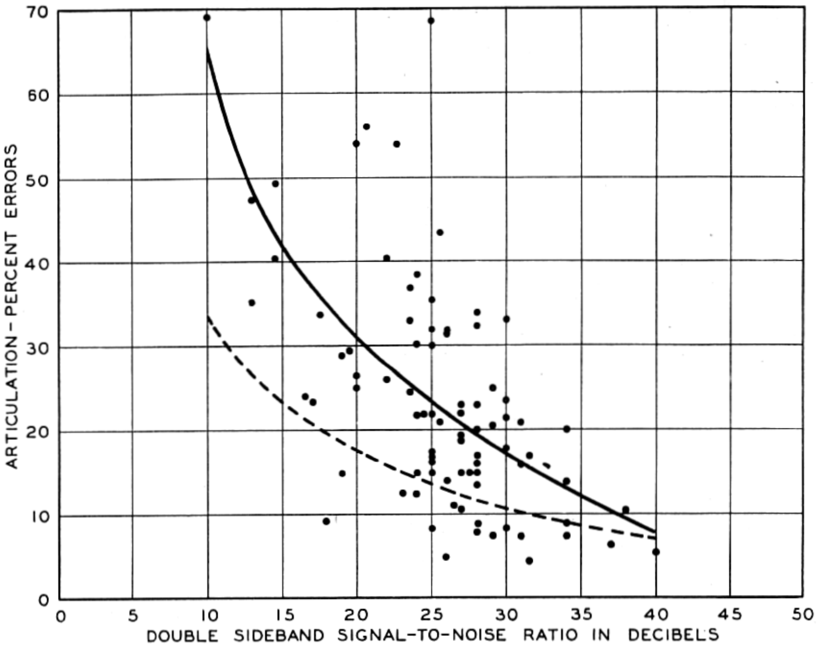

Fig. 13—Plot of per cent articulation errors on double-sideband vs. double-sideband signal-to-noise ratios.

Figures 14 and 15 show the circuit merits obtained on the single and double-sideband systems respectively plotted against the field strength measured on the double-sideband receiver. A circuit having a merit of 5 is an extremely good circuit, while a circuit having a merit of 3 is only just commercial and one having a circuit merit of 2 is useful only as an order wire. It will be noted that the difference between the curves for a circuit merit of 3 is about 8 db, for a circuit merit of 4 about 5.5 db, and for a circuit merit of 5 about 4.5 db. This is in fair agreement with the signal-to-noise and articulation data.

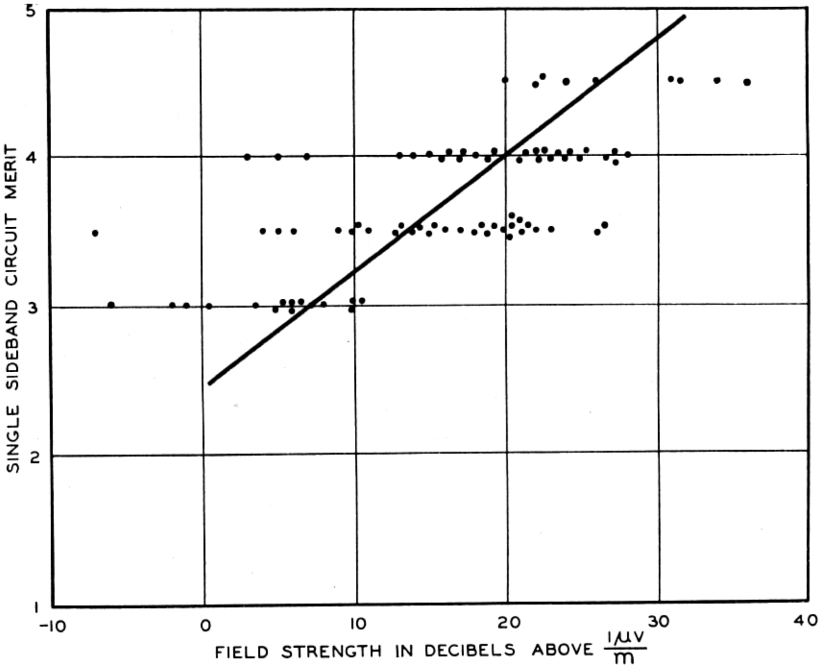

Fig. 14—Plot of circuit merit vs. field strength on single sideband.

The comparison of two circuits in this manner is undoubtedly of value if the observations extend over a period of time and if the individual observations are separated by a sufficient interval. When the observations are spaced at short intervals, however, the observer is bound to be influenced by the previous observation and it seems likely that the resulting comparison may be considerably in error. For instance, the observer may notice a small difference in circuit merit and consequently consistently rate one circuit a half point higher than the other, when the actual difference might be nearer to ¾ of a point. For this reason it is believed that the comparison of the two systems by means of circuit merit gives a less accurate result than by either signal-to-noise or articulation tests.

Outside of the general observation that, as might be expected, the improvement in signal-to-noise ratio at times when the circuit was poor was greater than at times when the circuit was good, no particular connection was found between the improvement obtained by the use of single-sideband and transmission conditions. Only one magnetic storm of any consequence occurred during the test and the transmission was so poor on that day that no results were obtained, and, therefore, no conclusions can be drawn as to the effect of magnetic storms.

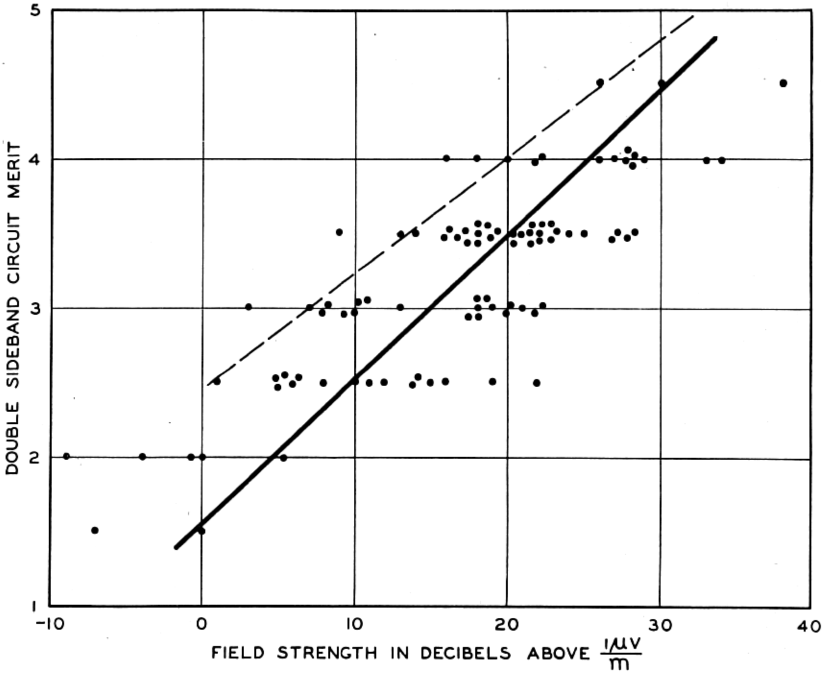

Fig. 15—Plot of circuit merit vs. field strength on double sideband.